NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

Editor:
Dat Duthinh[1]

Session secretaries:
Dat Duthinh[1]
John L. Gross[1]
Oscar Barton Jr.

Session chairs:
Hamid Saadatmanesh
Antonio Nanni
Orange Marshall

Session co-chairs:
Yan Xiao
Edward Fyfe
Mohammed Ehsani

[1]Structures Division
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-001

February 1999

NIST

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

Editor:
Dat Duthinh[1]

Session secretaries:
Dat Duthinh[1]
John L. Gross[1]
Oscar Barton Jr.

Session chairs:
Hamid Saadatmanesh
Antonio Nanni
Orange Marshall

Session co-chairs:
Yan Xiao
Edward Fyfe
Mohammed Ehsani

[1]Structures Division
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-001

February 1999

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Cheryl L. Shavers, *Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

DRAFT DESIGN GUIDELINES FOR CONCRETE BEAMS EXTERNALLY STRENGTHENED WITH FRP

by Hota V.S. GangaRao and P.V. Vijay

West Virginia University

Abstract: *This paper proposes guidelines for the design of concrete beams reinforced internally with steel and externally with FRP. The beam static response is described in terms of strength, stiffness, ductility / deformability, compositeness between wrap / plate and concrete, and associated failure modes.*

1 INTRODUCTION

Factors responsible for the deterioration of reinforced concrete structures leading to reduced service life include chemical aging e.g., corrosion, and load induced stresses greater than design stresses. To avoid the high cost of structural replacement, to maintain structural integrity, and to extend the performance of constructed facilities, viable rehabilitation schemes have been suggested (Ichimasu et al., 1993, Baluch et al., 1995, Oehelers D.J., 1992; Ziraba et al., 1994, Priestley et al., 1992; Plevris et al., 1995; Saadatmanesh and Ehsani, 1991, Meier et al., 1993).

Thin carbon or glass fabric in conjunction with resin constitute a durable combination against temperature, moisture, weathering and chemical attack (GangaRao et al., 1995) and can be easily wrapped on at least three sides of structurally deficient beams to improve structural performance. Carbon fabric wrapping can provide some additional advantages over conventional strengthening methods, such as: reduction in corrosion related damage; minimization of structural joints; improvement in mechanical and fatigue properties; and maintenance of member integrity under stress reversals (Meier et al., 1993).

Since many field applications of reinforcing concrete beams through wrapping/plating with CFRP composites are expected in the future, a set of preliminary design specifications are suggested here.

2 OBJECTIVE

The objective of this paper is to provide some preliminary design specifications of concrete beams wrapped/plated with CFRP composites and subjected to static bending, shear, creep and aging. A partial list of design guidelines concerning the external strengthening (wrap / plate reinforcement) of concrete beams using FRP is outlined below.

1. Increase in nominal flexural strength resulting from FRP wrap/plate .
2. Increase in stiffness before and after cracking of concrete and yielding of steel.
3. Decrease in steel reinforcement stress.
4. Change in composite action between wrap and concrete under varying loads.
5. Evaluate failure modes based on wrap configuration.
6. Provide moment and shear capacity formulation.

7. Provide creep coefficients of steel reinforced concrete beams wrapped with carbon.
8. Suggest knock-down factors for strength and stiffness under aging (accelerated vs. natural) accounting for temperature, moisture and pH variations.
9. Suggest accelerated aging methodology and calibrate results of composites under accelerated aging with naturally aged materials.
10. Provide guidelines on calculating deformability factors.

3 BENDING, SHEAR, CREEP AND AGING

3.1 Nominal flexural strength

- The fiber orientation of the composite plays a key role in the moment increase.
- Wrapping/bonding with fabric/plate at the soffit of the concrete beam is more effective than at the sides (flexural strengthening at the sides contributes less than 5 % to the overall moment increase, GangaRao and Vijay, 1998).
- The increase in the moment capacity caused by wrapping/bonding concrete beams with FRP composites is a function of the number of layers of the fabric. For a given concrete section and number of fabric layers, the increase in strength is higher for beams with lower steel reinforcement.

3.2 Increase in stiffness

- Wrapping leads to an increase in the stiffness of concrete beams accounted for by the stiffness of the FRP and its lever arm.
- Steel reinforced concrete beams exhibit high rotation or deflection with very little moment enhancement after steel yielding. Beams reinforced with FRP fabric exhibit controlled increase in deflection after steel yielding, since FRP has considerable strength left after steel has yielded (yield strain is 0.002 for Grade 60 steel, whereas FRP fabric/plate ultimate strain varies between 0.015 and 0.030).

3.3 Decrease in steel stress

- Reduction in steel stress can be calculated by treating the FRP fabric/plate as an additional reinforcement sharing the tensile forces with the steel reinforcement and contributing towards the overall force equilibrium.
- In estimating the stresses induced in the external FRP fabric/plate and the internal steel reinforcement, suitable consideration should be given to the modular ratios, strain-compatibility, linearity in strain distribution and geometric location of the internal and external reinforcements.

3.4 Composite action between FRP wrap/plate and concrete

- Unless otherwise specified, perfect composite action (implying no slip at the bond-line) can be assumed between FRP wrap/plate and concrete for computations on moment capacity, shear capacity, bond strength and short term deflections.

3.5 Failure modes based on wrap configuration

- FRP fabric/plate should preferably consist of fibers oriented parallel to principal tension, as in beam bending or column confinement. Alternatively, fibers should be oriented to address bi-directional stresses as in the case of a slab .

- Design for shear strengthening of a concrete beam with FRP fabric/plate should preferably consist of fibers orientated at $\pm 45^0$ to the beam axis. This external strengthening should be placed over the sides and the entire depth of the beam in the shear zone.

- Tension and compression failure in a flexurally strengthened beam can be calculated based on *c/D* approach (ratio of the compression depth to the total depth). For example, for a steel reinforced and carbon wrapped beam, balanced strain conditions exist at a *c/D* ratio of 0.17 (obtained by treating strains in concrete, Grade-60 steel and carbon fabric as 0.003, > 0.002 and 0.015 respectively). If the moment resistance is developed by force equilibrium having $c/D < 0.17$, then primary tension failure (i.e., steel yields and fabric ruptures) is to be expected. On the other hand, if the moment resistance is developed by a force equilibrium having $c/D > 0.17$, then secondary compression failure (i.e., steel yields followed by concrete crushing, but no steel or fabric/plate ruptures) is to be expected.

- If a beam is expected to fail in flexural tension, then localized fabric/plate rupture or debonding is to be expected at high fabric/plate strains in the tension zone. The wrapping of transverse layers helps to prevent fabric debonding.

3.6 Moment and shear capacity

- The mechanical properties of FRP strips should be established based on the available standards, e.g., ASTM D 3039 for the tensile strength of FRP strips.

- For tension failure of a concrete beam with external FRP wrap/plate, the neutral axis depth should be calculated in the same way as for any reinforced concrete beam by accounting for the contribution of tension provided by the FRP in addition to the existing steel reinforcement. For a singly reinforced beam,

$$c = \frac{a}{\beta_1} = \frac{A_{st} f_y + A_{FRP} f_{FRP}}{0.85 f_c' b} \qquad (1)$$

$$M_n = \left[A_{st} f_y \left(d - \frac{a}{2} \right) + A_{FRP} f_{FRP} \left(D + \frac{t_{FRP}}{2} - \frac{a}{2} \right) \right] \qquad (2)$$

where,

a	=	ACI rectangular stress block depth;
A_{st}	=	area of tension steel;
A_{FRP}	=	area of FRP;
β_1	=	0.65 to 0.85, based on f_c';
c	=	depth of neutral axis;
d	=	effective depth of beam without wrap/plate;

D = total beam depth;
f_y = steel yield stress;
f_{FRP} = FRP failure stress;
M_n = nominal moment and
t_{FRP} = thickness of FRP at beam soffit.

For compression failure in a beam with external FRP wrap/plate, the unknown FRP strain can be expressed in terms of neutral axis depth and ultimate concrete strain ($\varepsilon_c = 0.003$). Alternately, the unknown strains in the fabric/plate can be assumed and solved in a few iterations as given by the equations (3) and (4). By accounting for the flexural steel reinforcement (compression and tension), one obtains the neutral axis depth and nominal moment (GangaRao and Vijay, 1998).

$$\left(0.85 f_c' b\right) a^2 +$$

$$\left(0.003 E_s A_s' - A_s f_y - \sum_{i=1}^{3} (A_{FRP})^i (Avg.\varepsilon_{FRP})^i E_{FRP}\right) a - 0.003\beta_1 d'' E_s A_s' = 0 \qquad (3)$$

$$M_u = 0.85 f_c' ab\left(d - \frac{a}{2}\right) + A_s' f_s' (d - d'') + \sum_{i=1}^{3} (A_{FRP})^i (Avg.\ f_{FRP})^i d^i \qquad (4)$$

where,

A_s'	=	area of compression steel;
$(A_{FRP})^i$	=	area of the i^{th} segment;
$(Avg. f_{FRP})^i$	=	average FRP stress in the i^{th} segment;
$(Avg.\ \varepsilon_{FRP})^i$	=	average FRP strain in i^{th} segment.
b	=	beam width;
d^i	=	lever arm to the *ith* segment considered;
E_{FRP}	=	modulus of elasticity of FRP;
E_s	=	modulus of elasticity of steel;

- The shear capacity of a concrete beams wrapped with FRP fabric is given by:

$$V_{FRP} = A_{FRP}(E_{FRP}\varepsilon_{FRP})d \quad \text{for a fabric at } 0° / 90° \text{ layup} \qquad (5)$$

$$V_{FRP} = \sqrt{2} A_{FRP}(E_{FRP}\varepsilon_{FRP})d \quad \text{for a fabric at } 45° / 135° \text{ layup} \qquad (6)$$

where,

A_{FRP}	=	area of unit fabric length (length along longitudinal direction);
ε_{FRP}	=	0.005,
V_{FRP}	=	shear carried by FRP.

3.7 Creep coefficient of concrete beams wrapped with carbon fabric

- For estimating the creep strains and deflections of steel reinforced concrete beams wrapped with carbon fabric, the creep-coefficient (C_t) of an identical beam without wrap can be used with suitable reduction factors. For example, the creep reduction factor (f_{cw}) of carbon wrapped concrete beams is found to be 0.3 (Ligday, 1996).

$$C_t = \frac{\text{creep.strain}}{\text{initial elastic strain}} = f_{cw}(\gamma_c)C_u \qquad (7)$$

where, γ_c = combination of reduction factors given by ACI-209.

3.8 Knock-down factors for strength and stiffness under aging

Reductions in strength and stiffness of the FRP strengthened/rehabilitated concrete beams should be expected during the service life of the structure. Unless otherwise known, knock-down factors for strength and stiffness due to aging under the influence of temperature, stress, moisture and pH variations should be between 0.7 to 0.9 based on the severity of the related parameters.

3.9 Accelerated aging methodology and calibration

Accelerated aging methodologies can be used for predicting the long-term mechanical properties of FRP wrap/plate used for external strengthening of concrete beams. For example, correlation of such accelerated results with natural weathering under in-service conditions of a structure can be carried out with Proctor's (1985) accelerated aging methodology explained below:

STEP 1

Subject the composite specimens to either of the following conditioning scheme for 6 to 7 evenly spread different temperatures between T = 245 °K (-18 °F, low temperatures slow down aging but cause brittle failure) to T = 340 °K (150 °F, below glass transition temperature):

- Accelerated aging (wet conditioning);
- Accelerated stress corrosion.

STEP 2

Plot strength and stiffness loss curves (non-linear curves conforming to some power law, e.g., $S = S_o + mt^n$) versus aging period t.

STEP 3

Plot the curves in step 2 for an Arrhenius type relationship, i.e., $A = A_o \exp(-\Delta E/RT)$

- Plot the logarithm of the time to reach particular strength values, e.g., 600 MPa (87 ksi) or stiffness values, e.g., 45 GPa (6.5 Msi) versus the inverse of temperature.
- Repeat for various values of strength or stiffness to obtain a family of curves.

STEP 4

Normalize the curves in step 3 into 1 single curve by:

- Selecting a reference temperature, say 294 °K (70 °F).
- Plotting the ratio of the logarithm of the time taken by the composite strength or stiffness to fall to a given value at T °K to the logarithm of the time taken to fall to that value at the reference temperature, versus $1/T$. The time is read from the curves plotted in step 2.

STEP 5

- The normalized Arrhenius plot gives one overall picture of the relative acceleration of strength or stiffness loss at different temperatures.
- From the known time-scale shift (i.e., plot of Step 4), changes expected over long periods under lower service temperatures can be predicted by considering strength loss data from naturally weathered samples, mean annual temperature and other factors (say, moisture, freeze-thaw and pH level) as a basis for calibration.

3.10 Deformability / Ductility

The deformability index defined below can be used for evaluating the energy-absorbing characteristics of concrete beams reinforced with composite wrap/plate. The deformability index is the ratio of the energy or area under the moment-curvature curve at ultimate to that at a reference curvature which depends on the function of the structure, e.g., bridge deck versus building slab. The reference curvature should be limited to $0.006/d$, which is based on serviceability constraints of crack width and deflection, resulting in a deformability index of 4 or higher (GangaRao and Vijay, 1998, Vijay and GangaRao, 1997).

4 CONCLUSIONS

This paper proposed design guidelines for moment, shear, stiffness, creep, knock-down factors and deformability of concrete beams externally reinforced with FRP composites. These guidelines are based on research conducted at West Virginia University and other results referenced below.

REFERENCES

American Concrete Institute (1995), *Building Code Requirements for Reinforced Concrete and Commentary,* ACI 318R-95, Detroit, Michigan.

Baluch, M.H., Ziraba, Y.N., Azad, A.K., Sharif, A., Al-Sulamani, G.J and Basunbul, I.A. (1995), "Shear Strength of Plated RFC Beams," *Magazine of Concrete Research,* Vol. 47, No. 173, pp. 369-374.

Chajes, M.J., Januzska, T.F., Mertz, D.R., Thomson , T.A. Jr., and Flench, W.W., Jr. (1995), "Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics," *ACI Structural Journal,* Vol. 92, No. 3, pp. 295-303.

Chajes, M. J., Thomson, Jr., T. A., and Tarantino, B. (1995), "Reinforcement of concrete structures using externally bonded composite materials," *2nd Int. Symp. on Non-metallic (FRP) Reinforcement for Concrete structures (FRPRCS),* August 23-25, Ghent, Belgium.

Faza, S.S., and GangaRao, H.V.S. (1993), "Theoretical and Experimental Correlation of Behavior of Concrete Beams Reinforced with Fiber Reinforced Plastic Bars," *Fiber Reinforced-Plastic Reinforcement for Concrete Structures,* International Symposium, edited by Nanni, A. and Dolan, C.W., ACI SP-138, pp.599-614.

GangaRao, H.V.S. and Vijay, P. V. (1998), "Bending Behavior of Concrete Beams Wrapped with Carbon Fabric," *ASCE J. of Structural Engg.,* Vol. 124, No. 1, pp. 3-10.

GangaRao, H.V.S., Vijay P.V., and Dutta, P.K. (1995), "Durability of Composites in Infrastructure," *CORROSION-95,* Paper No. 550, The NACE International Annual Conference and Corrosion Show.

Ichimasu, H., Maruyama, M., Watanabe, H., and Hirose, T. (1993), "RC Slabs Strengthened by Bonded Carbon FRP Plates, Part-1 Laboratory Study and Part-2 Applications," *Fiber-Reinforced-Plastic Reinforcement for Concrete Structures,* International Symposium, Nanni, A. and Dolan, C.W., editors, ACI SP-138, pp. 933-970.

Jaeger, L.G., Tadros, G. and Mufti, A.A. (1995), "Balanced section, ductility and deformability in concrete with FRP reinforcement," Research Report submitted in Joint US - Canadian Meeting at West Virginia University.

Javed Sara, Kumar V.S. and GangaRao, H.V.S. (1996), "Experimental Behavior of Beams with Externally Bonded Carbon Fiber Tow Sheets," *Composites Institute 51st Annual Conference & Exposition '96,* pp. 3E1-3E7

Ligday F.J., Kumar S.V., and GangaRao H.V.S. (1996), "Creep of Concrete Beams with Externally Bonded Carbon Fiber Tow Sheets," *Advanced Composite Materials in Bridges and Structures 2nd Int. Conf.,* Montreal, Quebec, pp. 513-518.

Mander, J.B, Priestly, M.J.N., and Park, R. (1988), "Observed Stress-Strain Behavior of Confined Concrete," *ASCE J. of Structural Engineering,* Vol. 114, No. 8, pp.1827-1849.

Meier Urs, Deuring, M., Meier, H., and Schwegler, G. (1993), "Strengthening of Structures with Advanced Composites," *Alternative Materials for the Reinforcement and Prestressing of Concrete,* Clarke, J.L., ed., Blackie Academic and Professional, Chapman & Hall, Glasgow, pp. 154-171.

Meier, Urs (1992), "Carbon Fiber-Reinforced Polymers: Modern Materials in Bridge Engineering," *Structural Engineering International,* 1/92, International Association for Bridge and Structural Engineering, CH-8093, Zurich, Switzerland, pp. 7-12.

Muszynski, C. and Sierakowski, R. L. (1995), *50th Annual Conference,* Composites Institute, The Society of the Plastics Industry, Inc. January 30-February 1.

Neville, A.M. (1971): "Hardened Concrete: Physical and Mechanical Aspects", American Concrete Institute, pp.143-173.

Nikolaos, P., Triantafillou, T.C. and Veneziano, D. (1995), "Reliability of RC Members Strengthened with CFRP Laminates," *ASCE Journal of Structural Engineering*, Vol. 121, No. 7, pp. 1037-1044.

Oehlers, D.J. (1992), "Reinforced Concrete Beams with Plates Glued to their Soffits," *ASCE Journal of Structural Engineering*, Vol. 118, No. 8, pp. 2023-2038.

Priestly, M.J.N, Seible, F., and Fyfe, E. (1992), "Column Seismic Retrofit Using Fiberglass/Epoxy Jackets," *Advanced Composite Materials in Bridges and Structures*, edited by K.W. Neale and P. Labossiere, Canadian Society for Civil Engineering, pp. 287-298.

Proctor B.A. (1985), *The long-term Behavior of Glass Fiber Reinforced Composites,* Pilkington Publishers.

Rodriguez M. and Park, R. (1994), "Seismic Load Tests on Reinforced Concrete Columns Strengthened by Jacketing," *ACI Structural Journal*, Vol. 91, No. 2, pp. 150-159.

Saadatmanesh, H., and Ehsani, M.R. (1991), "RC Beams Strengthened with GFRP Plates-I, Experimental Study," *Journal of Structural Engineering*, Vol. 117, No. 11, pp. 3417-3433.

Tonen Corporation (1994), *Forca Tow Sheet Process Application Guidelines,* Japan

Vijay P.V., Kumar S.V., and GangaRao H.V.S. (1996), "Shear and Ductility Behavior of Concrete Beams Reinforced with GFRP Bars," *Advanced Composite Materials in Bridges and Structures 2nd Int. Conf.,* Montreal, Quebec, Canada.

Vijay P.V. and GangaRao H.V.S. (1996), "A Unified Limit State Approach Using Deformability Factors in Concrete Beams Reinforced with GFRP Bars", *Materials for the New Millennium*, ASCE 4th Material Conf., Vol. 1, Washington D.C., pp. 657-665.

Ziegahn, K.-F., Krause, H. H. and Schmitt, D. (1989), "Effects of Airborne Pollutants on Deterioration and Aging Behavior of Materials," *J. Environmental Sciences,* March/April.

Ziraba, Y.N,, Baluch, M.H., Basunbul, I.A., Sharif, A.M., Azad, A.K., and Al-Sulaimani, G.J. (1994), "Guidelines Toward the Design of Reinforced Concrete Beams with External Plates," *ACI Structural Journal*, Vol. 91, No. 6, pp. 639-646.